Acknowledgement

The slides used this semester are derived from slides originally prepared by the textbook authors, Randall Bryant and David O’Hallaron.

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Abstraction is our Friend

Most of what we study in Computer Science is really about a hierarchy of abstractions! Without abstraction, we wouldn’t be able to accomplish much.
Abstraction vs. Reality

**Abstraction is good, but don’t forget reality!**

Most of your courses to date have emphasized abstraction.
- High level programming languages
- Abstract data types
- Asymptotic analysis

These abstractions have limits!
- Especially in the presence of bugs
- Need to understand underlying implementations
- Need to have a working understanding of architecture

**Desired Outcomes**

Useful outcomes!
- Know “stuff” that all computer scientists should know
- Become more effective programmers
  - Able to find and eliminate bugs efficiently
  - Able to tune program performance
- Prepare for later “systems” classes: Compilers, Operating Systems, Networks, Computer Architecture, Embedded Systems, many others.

**Hint:** Hang onto your book. You’ll be using this same book (3rd edition) in CS439.

**Great Reality 1**

**Ints are not Integers; Floats are not Reals.**

<table>
<thead>
<tr>
<th>+</th>
<th>0110 1000 101 0110 0100 0011 0100 0010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sign:</td>
<td>0 =&gt; positive</td>
</tr>
<tr>
<td>Exponent:</td>
<td>0110 1000 101 0110 0100 0011 0100 0010</td>
</tr>
<tr>
<td>- Bias adjustment:</td>
<td>104 - 127 = -23</td>
</tr>
<tr>
<td>Significant:</td>
<td>$1 + 2^2 + 3^2 + 2^2 + 3^2 + 2^2 + 3^2 + 4^2 + 2^{15} + 2^{16} + 2^{17} + 2^{22}$</td>
</tr>
<tr>
<td>Represents:</td>
<td>$1.666115<em>2^{-22} \approx 1.986</em>10^{-7}$</td>
</tr>
</tbody>
</table>

Is $x^2 \geq 0$? For floats, yes. For ints, not necessarily.

- $40000 * 40000 \rightarrow 16000000000$
- $50000 * 50000 \rightarrow ??$

- $40000 \times 40000 \rightarrow 16000000000$
- $50000 \times 50000 \rightarrow ??$

**Floats are not Reals**

Is $(x + y) + z = x + (y + z)$? For int’s: yes. For floats, maybe not.

- $(1e20 + -1e20) + 3.14 \rightarrow 3.14$
- $1e20 + (-1e20 + 3.14) \rightarrow ??$
Treat CS as an Experimental Science

Get into the habit of writing programs to experiment with the architecture:

```c
void main() {
    printf("40000 * 40000 = %d\n", 40000 * 40000);
    printf("50000 * 50000 = %d\n", 50000 * 50000);
    printf("1e20 + (-1e20 + 3.14) = %f\n", 1e20 + (-1e20 + 3.14));
    printf("(1e20 + -1e20) + 3.14 = %f\n", (1e20 + -1e20) + 3.14);
}
```

> gcc tester.c
> a.out
40000 * 40000 = 1600000000
50000 * 50000 = -1794967296
1e20 + (-1e20 + 3.14) = 0.000000
(1e20 + -1e20) + 3.14 = 3.140000

Great Reality 2

**Computer scientists should understand assembly language!**

You won't often program in assembly. Compilers are much better at it and more patient than you are.

Understanding assembly is key to understanding what really happens on the machine.

- Behavior of programs in presence of bugs; high-level language model breaks down.
- Tuning program performance and understanding sources of program inefficiency.
- Implementing system software
  - Compiler has machine code as target
  - Operating systems must manage process state
- Creating / fighting malware: x86 is the language of choice for attackers.

Great Reality 3

**Memory Matters!**

Memory is not unbounded!

- It must be allocated and managed.
- Many applications are memory dominated.

Memory referencing bugs are especially pernicious. The effects may be distant in both time and space.

Memory performance is not uniform.

- Cache and virtual memory effects can greatly affect program performance.
- Adapting your programs to characteristics of memory system can lead to major speed improvements.
Memory Referencing Bug Example

double fun(int i)
{
    int a[2];
    double d[1] = {3.14};
    a[i] = 1073741824;
    return d[0];
}

Assume x86 (double is 8 bytes; int is 4 bytes). This will be different on other systems, and may cause segmentation fault on some.

Word Representation

<table>
<thead>
<tr>
<th>Call</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>fun(0)</td>
<td>→ 3.14</td>
</tr>
<tr>
<td>fun(1)</td>
<td>→ 3.14</td>
</tr>
<tr>
<td>fun(2)</td>
<td>→ 3.1399998664856</td>
</tr>
<tr>
<td>fun(3)</td>
<td>→ 2.00000061035156</td>
</tr>
<tr>
<td>fun(4)</td>
<td>→ 3.14, then segmentation fault</td>
</tr>
</tbody>
</table>

What can you infer about how the memory is laid out?

Memory Referencing Bug Explanation, Little Endian

double fun(int i)
{
    int a[2];
    double d[1] = {3.14};
    a[i] = 1073741824;
    return d[0];
}

Modified Call Result

<table>
<thead>
<tr>
<th>Call</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>a[0]</td>
<td>fun(0) → 3.14</td>
</tr>
<tr>
<td>a[1]</td>
<td>fun(1) → 3.14</td>
</tr>
<tr>
<td>d3...d0</td>
<td>fun(2) → 3.1399998664856</td>
</tr>
<tr>
<td>d7...d4</td>
<td>fun(3) → 2.00000061035156</td>
</tr>
<tr>
<td>saved state</td>
<td>fun(4) → 3.14, then seg fault</td>
</tr>
</tbody>
</table>

C and C++ do not provide much memory protection.
- Out of bounds array references
- Invalid pointer values
- Abuses of malloc/free

This can lead to nasty bugs.
- Whether or not bug has any effect depends on system and compiler.
- Action at a distance
  - Corrupted object logically unrelated to one being accessed.
  - Effect of bug may be first observed long after it is generated.

How can I deal with this?
- Program in Java, Lisp, or ML
- Understand what possible interactions may occur
- Use or develop tools to detect referencing errors

Memory Performance Example

The following copies an \( n \times n \) matrix:

```c
/* i j */
for (i=0; i<n; i++) {
    for (j=0; j<n; j++) {
        b[i][j] = a[i][j];
    }
}
```

This one computes precisely the same result.

```c
/* j i */
for (j=0; j<n; j++) {
    for (i=0; i<n; i++) {
        b[i][j] = a[i][j];
    }
}
```

But the performance may be much (could be 10X) slower, particularly for large arrays. Can you guess why that may be?
Great Reality 4

**There’s more to performance than asymptotic complexity.**

**Constant factors matter too!**
- Even an exact op count does not predict performance.
- Easily see 10:1 performance range depending on how code is written.
- Must optimize at multiple levels: algorithm, data representations, procedures, and loops.

**Must understand the system to optimize performance.**
- How programs are compiled and executed.
- How to measure program performance and identify bottlenecks.
- How to improve performance without destroying code modularity and generality.

Great Reality 5

**Computers do more than execute programs.**

They need to get data in and out. The I/O system is critical to program reliability and performance.

They communicate with each other over networks. Many system-level issues arise in the presence of networking:
- Concurrent operations by autonomous processes
- Coping with unreliable media
- Cross platform compatibility
- Complex performance issues

Great Reality 6 (I Added this One)

**Computers do a lot with very simple primitives.**

Nobel Prize winner (in Economics) Herbert Simon used an ant to explain how simple actions can explain complex results. (*Sciences of the Artificial*, 1969)

Imagine an ant walking along a beach. You notice that the ant is tracing a very intricate path. Must be executing a pretty complex algorithm, right?

**Lesson:** You can generate very complex results using only very simple tools.

Simon’s Ant
Church-Turing Thesis

A Turing Machine is a very simple computing device that can look at a symbol on a tape, write another symbol, and move right or left one square, under the direction of a simple program.

Everything that can be computed can be computed by a Turing Machine.

The most powerful computer you’ll ever use in your life is no more powerful than a Turing Machine. We say that a machine is Turing complete if it can emulate a Turing machine.

Course Perspective

Most systems courses are “builder-centric.”

- Computer Architecture: Design pipelined processor in Verilog.
- Operating Systems: Implement large portions of operating system.
- Compilers: Write compiler for simple language.
- Networking: Implement and simulate network protocols.

This course is programmer-centric.

- The purpose is to show how by knowing more about the design of the underlying system, one can be more effective as a programmer.
- Enable you to
  - Write programs that are more reliable and efficient
  - Incorporate features that require hooks into OS: concurrency, signal handlers, etc.
- Not just a course for dedicated hackers. We bring out the hidden hacker in everyone.
- Cover material in this course that you won’t see elsewhere.